There are Orders-of-Magnitude Power Advantages in Complementing the Transistor With a Milli-Volt Switch

MTO Symposium
San Jose, CA, March 7, 2007

Eli Yablonovitch
UCLA EE Dept.
& UC Berkeley EECS Dept.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **07 MAR 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED -

4. TITLE AND SUBTITLE **There are Orders-of-Magnitude Power Advantages in Complementing the Transistor With a Milli-Volt Switch**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **UCLA EE Dept.**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
DARPA Microsystems Technology Symposium held in San Jose, California on March 5-7, 2007. Presentations, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Read the current going through a resistor, in the presence of noise:

$$(\Delta i)^2 = 2q\, i \times \Delta f \text{...........Shot Noise}$$

$$(\Delta i)^2 = \frac{4kT}{R} \times \Delta f \text{..........Johnson Noise}$$

$$\text{Required voltage } V = iR >> 2kT/q \sim 50\text{mVolts}$$

$$\text{Signal} - \text{to} - \text{Noise Ratio} = \frac{i}{\sqrt{2q\, i\Delta f}} = \sqrt{\frac{i}{2q\, \Delta f}}$$

$$i > 2q \times \Delta f$$

$$\text{Required power } iV > 2q\, \Delta f \times \frac{2kT}{q} = 4kT \times \Delta f$$

With a safety margin:

Energy Consumed ~ 40 kT per bit processed

What will be the energy cost, per bit processed?

1. Logic — energy cost ~40kT per bit processed
2. Storage — energy cost ~40kT per bit processed
3. Communications — currently >100,000kT per bit processed

.

There are many type of memory possible:

1. Flash
2. SRAM
3. Dram
4. Magnetic Spin
5. Nano-Electro-Chemical Cells
6. Nano-Electro-Mechanical NEMS
7. Moletronic
8. Chalcogenide glass (phase change)
9. Carbon Nanotubes
    -
    -

Similarly there are many ways to do logic.

But there are not many ways to communicate:

1. Microwaves (electrical)
2. Optical

What is the energy cost for electrical communication?

$$V_{noise}^2 = 4kT\,R\,\Delta f$$

$$\frac{V_{noise}^2}{R} = 4kT\;\Delta f$$

Signal Energy $\geq$ Noise Power per bit $=$ $4kT$ per bit

All information processing costs ~ 40kT per bit.

(for good Signal-to-Noise Ratio)

Great!

So what's the problem?

The transistor will have to be replaced by a 1milli-Volt switch:

The natural voltage range for wired communication is rather low:

$$V_{noise}^2 = 4kT\,R\,\Delta f$$

$$V_{noise}^2 = 4kT\,R\,\frac{1}{RC}$$

$$V_{noise}^2 = 4kT \times \frac{1}{C}$$

$$V_{noise}^2 = \frac{4kT}{q} \times \frac{q}{C}$$

$$V_{noise} = \sqrt{\underbrace{4kT/q}_{100\text{mVolts}} \times \underbrace{q/C}_{10\mu\text{Volts}}}$$

$$V \approx 1\,\text{mVolt}$$

The wire wants
1000 electrons at 1mVolt each.

(to fulfill the signal-to-noise requirement >1eV of energy)

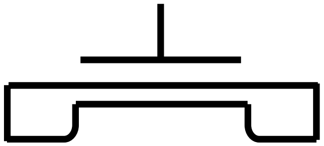
The natural voltage range for a thermally activated switch like transistors is >>kT/q, eg. ~ 40kT/q or about ~1Volt

Voltage Matching Crisis
at the nano-scale!

If you ignore it the penalty will be
$(1\text{Volt}/1\text{mVolt})^2 = 10^6$

The thermally activated device wants at least one electron at ~1Volt.

A low-voltage technology, or an impedance matching device, needs to be invented/discovered at the Nano-scale:



transistor amplifier with
steeper sub-threshold slope

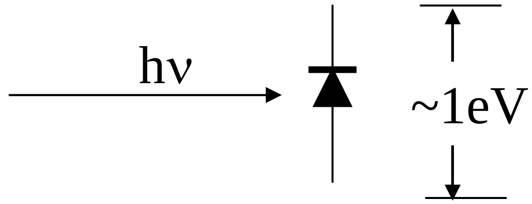
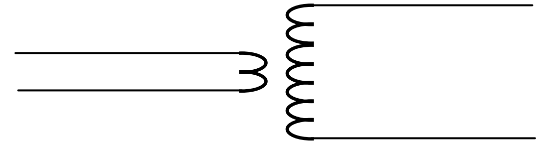
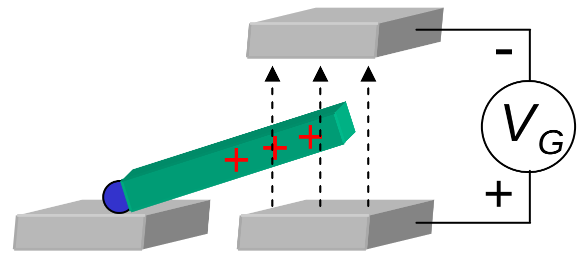


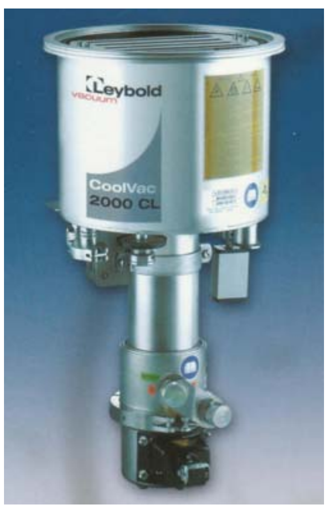
photo-diode



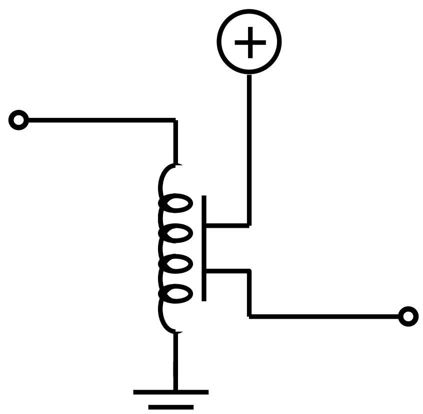
nano-transformer



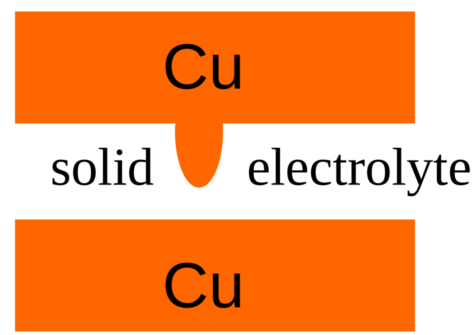
MEM's switch



Cryo-Electronics
kT/q~q/C



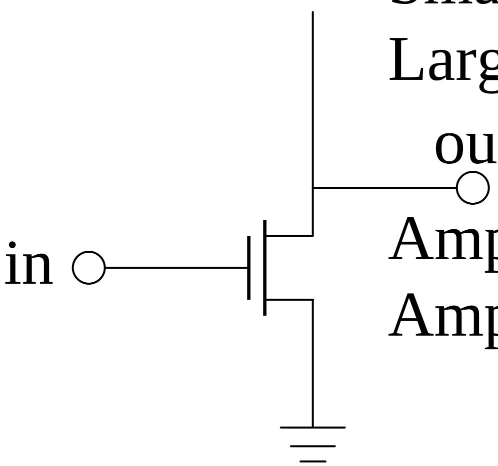
giant magneto-resistance
spintronics



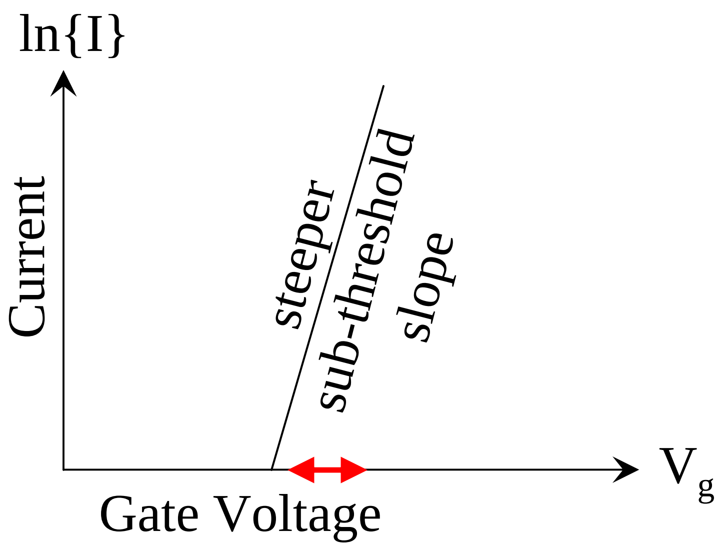
Electro-Chemical Switch

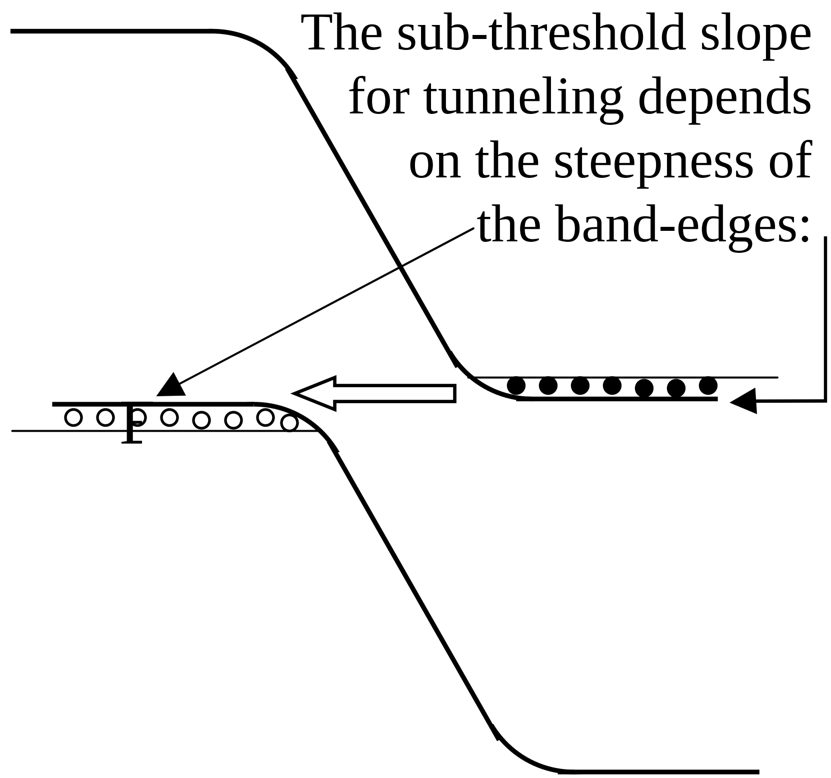
An amplifying transistor as a voltage matching device:

Small voltage in
Large voltage out

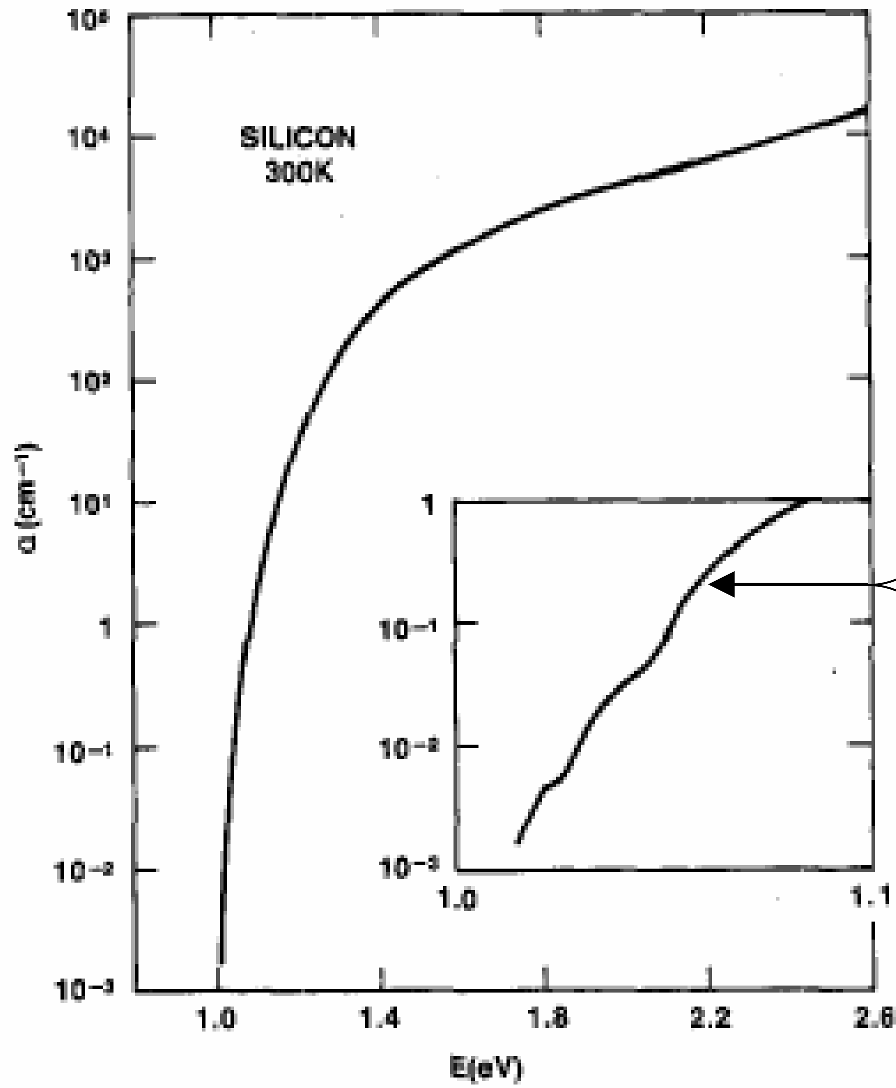


Amplification of weak signals has an energy cost!
Amplification of weak signals has a speed penalty!





The optical absorption coefficient, $\alpha(h\nu)$, of Si at 300K, in the vicinity of the band edge.



Tom Tiedje, Eli Yablonovitch, George D. Cody, and Bonnie G. Brooks
IEEE Trans. On Elec. Dev., VOL. ED-31, NO. 5 , p. 711 (MAY 1984)

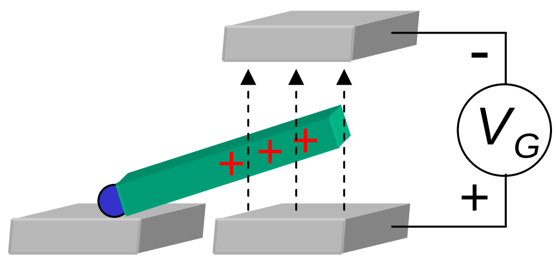
The Urbach edge grows as:
$\alpha(h\nu) \sim \exp\{(h\nu - E_g)/E_o\}$,

where the E_o parameter is a type of sub-threshold slope.

$E_o \sim 10$meV for Silicon

It's good, but it should be better.
We need to search for materials with steeper band-edges!

Nano-Mechanical Switch:



$$I \sim \exp(-3qV_G/kT)$$

for 3 charges on the MEM's tip

After M. A. Baldo

Recommendations:

1. Medium and long-range internal communication is beset by a Voltage Matching problem, leading to severe energy inefficiency.

2. The transistor will have to be replaced by a 1milli-Volt switch:

3. Metallic or semi-metallic switches are likely to be more radiation hard.

4. Band edge steepness is poorly known, and should be investigated for a number of semiconductors and semi-metals.

5. How will the world change if the energy/bit-function drops by six orders of magnitude?